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The Air Force identified measuring stresses in hard-to-access locations as a major concern. Detrimental stresses in these locations lead to expensive loss of use, inspection & repair costs, and potential loss of aircraft and personnel. Aluminum alloys were the structural materials identified as the highest interest of the Air Force. A small XRD system named MAX (Miniature Advanced X-Ray) was developed to fit inside a 6" orifice. MAX is a very portable XRD system that can make quality residual stress measurements quickly in hard-to-access locations on aircraft. The system can be carried by one person and configured for measurements in less than 5 minutes. The user-friendly software controls the system and has a powerful peak analysis routine. Comparison of MAX's data to other XRD systems show that residual stress measurements are reliable.

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INTRODUCTION

The Air Force identified a need for a small x-ray diffraction (XRD) device that would measure residual stresses in hard-to-access locations. Aluminum alloys were the structural materials identified as the highest interest of the Air Force.

A successful Phase I effort indicated that a small XRD system could be developed that would fit inside a 6" orifice. The conceptual design successfully measured stresses in aluminum alloys. The Phase II effort implemented the concept into a working prototype. This system, named MAX (Miniature Advanced X-ray), evolved during this project. The details of this development are reported.

WORK PLAN

The work plan for this project was divided into 12 tasks as shown below.

1. Identify x-ray wavelengths and calculate 2θ and β angles.
2. Design, assemble and test the head
3. Design, assemble and test the electronics
4. Fabricate and obtain the components
5. Obtain representative samples
6. Write and test the software and firmware
7. Build and test systems
8. Design the packaging
9. Design the fixtures
10. Refine the prototype system
11. Provide a prototype system to the Air Force
12. Prepare the Phase II final report

Identify X-ray Wavelengths and Calculate 2θ and β angles.

Previous work identified copper radiation at approximately 160^0 2θ as optimum condition for measuring aluminum alloys. This configuration accomplished two objectives. First, precision measurements could be made on aluminum alloys due to the high back reflection angle. Second, the overall size of the head could be reduced since the detectors could be mounted against the x-ray tube. A modified TEC 4000 system confirmed this configuration. Initial results using a miniaturized Moxtek x-ray tube indicated the center of the peak actually occurred at about 161^0 2θ. Since the Moxtek tube had been selected for the prototype system, 161^0 2θ was selected for the first head design.

Moxtek also supplied chromium x-ray tubes to TEC for use in measuring steels and nickel alloys. Ferritic and martensitic steel have diffraction peaks at approximately 156^0 2θ, while austenitic steels and most nickel alloys have peaks at 128^0 2θ using chromium x-rays. The lower 128^0 2θ position, while not optimum should produce acceptable results. Moxtek was contacted to see if they could provide manganese radiation which would increase the peak positions for austenitic steels and nickel alloys. Currently Moxtek does not offer this radiation.

Since titanium alloys were identified as important materials for aircraft, a configuration was selected for measuring stresses in these alloys. Copper radiation at 142^0 2θ works well for common alloys such as Ti-6-4.

For all of the above cases β angles were selected to position the right-side detector at 40^0 - 46^0 ψ. A 0^0 β angle was selected for detector calibration.

Testing of coldworked aluminum samples during the later stages of this project lead to another redesign of the 161^0 2θ head. Coldworked samples generally have broad peaks in addition to high stresses. It was determined that centering the detector at 163^0 2θ would permit precise measurements on low and high stress aluminum components that had narrow or broad peaks.

Design, Assemble and Test the Head

The objective of this task was to design a unibody structure that would hold the x-ray tube and two detectors at the correct angles for stress measurements and fit inside a 4.5" opening. The design engineer concluded that the detector housings would need to be redesigned to accomplish this objective. Preliminary testing had used two position-sensitive proportional counter (PSPC) detectors from the TEC 4000 XRD System. These detectors could be used, but the x-ray head would enlarge to a 6" size.

A decision was made to redesign the TEC 4000 detectors. The new PSPC detectors maintained a 1" detection window with the associated electronics relocated to the side. This redesign reduced the overall height of the detectors and allowed a 4.5" head to be built.

The preliminary fixture was designed and built. Initial testing gave promising results on aluminum alloys. Work began on calibration software routines. The calibration routines pointed to a need for redesigned detector electronics. This information will be discussed in the next section.

Late in the second year of his project, Moxtek redesigned their x-ray tube to add more shielding. This change forced additional changes to the unibody fixture. The latest design, incorporated into the system to be delivered to the Air Force, has been enlarged to 5" to accommodate the current Moxtek x-ray tube.

Design, Assemble and Test the Electronics

The original plan for this task was to modify existing TEC 4000 detector electronics for use in MAX. During the detector calibration and testing phase, it was determined that adjustments would be needed to match the electronics to the detectors. The necessary adjustments were not possible with the TEC 4000 detectors for consistent output results. A decision was made to redesign the electronics based on a NIM bin technology used in the TEC 1630 System. The redesigned electronics had the benefits of being much smaller and light-weight and allowing adjustments specific to an individual detector. This development is considered one of the major contributions of this project.

The TEC 1630 NIM bin has dimensions of 18" x 21" x 9" and weighs 38 pounds. The MAX detector electronics consists of IC boards with dimensions of 7 1/2" x 7 1/2" x 1/2" and weighs less than a pound.

Once the electronics were designed and tested, testing of the MAX prototype began. An electronic noise problem developed. This noise was traced to the x-ray tube power supply. The original design x-ray tubes were returned to Moxtek to correct this problem. The x-ray tube used in the Air Force's system does not produce this noise.

A safety system was incorporated into the MAX electronics package. The system consists of a light beam and reflector which connects to circuitry. The light beam acts as a safety barrier to prevent body parts form entering a radiation area at the MAX head. The circuitry works as an interlock to turn off the x-rays if the light beam is disturbed.

Fabricate and Obtain the Components

This task started once components were identified and designs were completed.

Obtain Representative Samples

The initial testing was performed on 2024, 6061, and 7075 Al samples provided by Warner Robins AFB. Additional testing was performed on aluminum and ferrite stress-free powders. These results were compared to baseline results measured by the TEC 1630 System. Results using MAX were comparable on all samples. Data acquisition times ranged from 1 to 5 min. These times compare to 5 to 20 min. used by the TEC 1630.

A more complex-geometry part was sent to TEC by Warner Robins. This part had cylindrical and flat surfaces. A flat surface was identified as the main location of interest. Measurements in both locations were possible with MAX.

In early 2005, aluminum coldworked hole standards were sent to TEC by Wright-Patterson AFB. These samples were measured extensively by a TEC 1630 and MAX. In about half the cases, the results agreed. For the other cases, disagreement was attributed to peak analysis problems. The peak analysis routines are being upgraded to address this concern.

Write and Test the Software and Firmware

Since MAX is a new system, software code from the TEC 1630 and 4000 Systems was not used except for the data analysis routines. Thus, software and firmware development was a major task for this project.

The software was developed using Microsoft Visual Basic and Visual C. It operates on Windows XP operating system. The software controls all aspects of making stress measurements other than positioning the measurement head. In addition to manual settings on the detector electronics, the software can be used to make changes needed for detector calibration.

The user interface consists of three tabs. The first step includes inputting measurement parameters such as measurement time, power levels, elastic constant, and sample description. The second tab shows the data acquisition screen in which the data are displayed in real time. The third tab opens up the analysis routine and displays the results.

The analysis program has some unique and powerful features such as manual background selection, user selectable peak fitting routines, and peak analysis displays. Error analysis based on counting statistics is displayed along with the results.

The safety system is under software control. If the interlock beam is broken, the software turns off the x-rays and requires acknowledgement from the user before allowing a measurement to start or resume.

An operator's manual has been written which details setting up the system, how to take measurements, and how to run the software.

Build and Test Systems

The components of the system were tested where possible prior to integrating them into the finished product. Because of this process most problems were found and corrected prior to final assembly. Once the system was assembled, testing proceeded smoothly.

Design the Packaging

Because portability was an important consideration, packaging was critical to the overall success and acceptance of MAX. Two briefcase-sized, hard shelled cases were selected. The electronics were packaged in one case while the measurement head, cabling, high voltage power supply and safety system light beam were packaged in the other. With the addition of a laptop computer, MAX is a complete self-contained system that can be carried by a single person.

The system was shipped by airline to Tinker AFB in October 2004. Upon return to TEC, the system was checked for damage. A power supply case in the electronics enclosure had cracked. This problem was repaired and additional supports were added to prevent reoccurrences.

Cable connections are labeled enabling MAX to be configured and readied to take measurements in less than five minutes. Disconnecting and shutting down the system at the end of a job can be accomplished as quickly.

Design the Fixture

The current MAX measurement head consists of a vertical plate that hold the detectors/x-ray tube assembly at the correct position for calibration and measurement. This vertical plate attaches to a horizontal foot that is used to position the x-ray tube over the measurement location. Due to the light weight of the measurement head, clamps or tape can be used across this horizontal foot to hold MAX in place in any orientation.

Currently, the horizontal foot is intended for use on flat surfaces. Additional feet can be designed for use with other geometries. Customized feet can also be built for unusual geometries.

For commercialization a universal fixturing system may be considered. Details will be presented in the commercialization section.

Refine the Prototype System

During the initial testing phase, several components were identified and changed to improve the system. These components included the measurement head for aluminum alloys, which was changed to 163^0 2θ. The detectors were redesigned to fit inside a smaller housing, and new detector electronics were developed. Other features have been identified for improvements. These will be presented in the commercialization section

Provide a Prototype System to the Air Force

The prototype system has been built and tested and is ready for delivery to Warner Robins AFB. This system consists of a Moxtek copper x-ray tube and 163^0 2θ and 142^0 2θ measurement heads. These measurement heads can be used to measure aluminum and titanium alloys. The system also includes the software required to operate the system. This software is installed on a laptop computer. A user-friendly operating manual will also be supplied.

Prepare the Phase II Final Report

This final report describes the development of MAX. The following section will discuss future enhancements that are being considered for MAX.

COMMERCIALIZATION

MAX is a very powerful analytical tool that meets the Air Force's requirements for measuring residual stress in hard-to-access locations on aircraft. Emphasis has been placed on using MAX to measure aluminum alloys. During this project several potential improvements have been identified which should enhance MAX's commercial appeal.

The Air Force identified various alloys, in addition to aluminum, that would be of interest for measurement capability. These include ferritic, martensitic, and austenitic steels, titanium alloys, and nickel alloys. Austenitic steels and nickel alloys could be measured with a chromium tube using a 128^0 2θ measurement head. They could potentially be measured with chromium Kβ radiation using a 156^0 2θ measurement head. The use of manganese radiation at 156^0 2θ is a third possibility. The current MAX system could be tested on these alloys using chromium radiation. At this date, Moxtek does not supply a manganese x-ray tube. Manganese radiation is a desirable future enhancement.

A universal positioning device is also desirable. The current system can be adapted to a large number of geometries by making several positioning feet. A tripod-type positioning system could expand MAX's ability to measure a larger number of different geometries without the need of a customized fixture.

In cases where broad peaks are encountered along with large peak shifts associated with high stresses, there may be a need for a detector with a larger window. Potential design changes have been proposed, but these changes enlarge the overall size of MAX. By expanding MAX to a 6" height, detectors with large windows are possible. This new design may be required when high stresses are expected.

A battery-powered system would be desirable for using MAX in remote locations. Initial investigation into this possibility revealed several concerns. Grounding of the x-ray tube is the highest concern at this point. Other issues such as battery size and life would need to be addressed.

CONCLUSIONS

MAX is a very portable XRD system that can make quality residual stress measurements quickly in hard-to-access locations on aircraft. The system can be carried by one person and configured for measurements in less than 5 minutes. The user-friendly software controls the system and has a powerful peak analysis routine. Comparison of MAX's data to other XRD systems show that residual stress measurements are reliable.

Further enhancements have been recommended. These include procuring a miniature manganese x-ray tube, designing a universal positioning system, and enlarging the detector windows. Converting the system to battery operation could enhance MAX's usefulness in remote locations.